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Study of Site Effect at Seismic Station Located in Undermined Area of Karviná Region (Czech Republic)

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Abstract

The Karviná region is well known as an area with an intensive mining induced seismicity. The local geological pattern, especially subsurface sedimentary layers, belongs to one of the most important factors that influence the amplification of seismic effect on the surface. In order to investigate the amplification effect, there are used methods of spectral ratio that enable to analyse records of vibrations. In the present study, two methods, signed as SSR (standard spectral ratio) and HVSR (horizontal to vertical spectral ratio), were used for the site effect evaluation. The analysis was performed in the populated Doubrava locality where high seismic loading on the surface due to mining induced seismicity is documented.

Key words: Karviná region, site effect, SSR, HVSR, mining induced seismicity.

1. INTRODUCTION

Mainly in seismically active areas, the evaluation of seismic loading of buildings is an integral part of the city planning and project documentation either in case of new building design or a reconstruction of existing ones. In addition to the parameters of buildings, the characteristics of the foundation soil play an important role when evaluating seismic loading and its effects of the given locality. It is generally known that local geological conditions may

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influence seismic effect on the surface, either increasing or decreasing it. Just in built-up areas, the amplification of seismic effect on the surface increases the risk of a building damage.

The ground motion, which may be recorded on the free surface of a terrain, is influenced by three factors: source mechanism, seismic wave propagation to the bedrock interface below the investigated site, and site effects. The first two factors define the kind of seismic input whereas the third one represents all the modifications that might occur as a consequence of the interaction between seismic waves and local characteristics of an investigated site, especially the physical and mechanical properties of subsurface geology, the presence of heterogeneities and discontinuities, the morphologic and stratigraphic features of terrain (Panzera *et al.* 2013).

The study of a site effect is mainly connected with the localities in source areas of natural earthquakes. However, this effect can also be investigated in the surroundings of other sources of seismic loading in built-up areas. Mining induced seismicity caused by underground exploitation is one case of such loading. A number of authors have dealt with the evaluation of site effect in undermined areas (*e.g.*, Olszewska and Lasocki 2004, Lurka and Stec 2005, Kaláb and Knejzlík 2006, Holečko and Koníček 2007, Frej and Zuberek 2008, Driad-Lebeau *et al.* 2009, Semblat *et al.* 2010, Lasocki 2013, Adámek and Holečko 2014).

This paper deals with the use of two different spectral ratio methods and their comparison in order to be able to evaluate the site effect in Doubrava locality in the Karviná region, the Czech Republic, where the exploitation of black coal and mining induced seismicity is still active. The first study by means of spectral ratio methods was performed in the Karviná region by Kaláb and Knejzlík (2006) on the records of mining induced seismic events generated in the Ostrava–Karviná Coalfield (OKC). Next studies were performed both on the records of mining induced seismic events generated in the OKC as well as on the records of seismic noise measured in the Karviná region, *e.g.*, Kaláb and Lyubushin (2008), Lednická and Kaláb (2014), Lednická (2015). The results, gathered in selected parts of the Karvina region, confirmed the possibility of using these methods while investigating the seismic effect amplification in sedimentary layers. The authors have found out that the spectral ratio exhibits no significant peaks in Orlová locality where the outcrop of Carboniferous bedrock is located. But in other investigated localities, covered by sedimentary layers, spectral ratio demonstrates significant peaks. It was documented, *e.g.*, in Stonava locality that the resonant frequencies calculated from the seismic records at permanent seismic stations and the resonant frequencies obtained by analysis of seismic noise measurements are represented by the spectral ratio peak of about 1-2 Hz. In other localities, two or more peaks were often detected which indicates a complexity of subsurface layers in the studied places. More peaks were detected also in records from Doubrava locality (Kaláb and Knejzlík 2006); therefore, it was selected for this additional study.

2. SITE DESCRIPTION

The Upper Silesian Coal Basin (USCB) spreads out partly in the Czech Republic and in Poland, where its bigger part is located. The OKC, which is the Czech part of the USCB, lies in the northeastern territory of the country. Black coal has been exploited there in underground mines for more than 200 years and intensive mining induced seismicity has also been documented there (*e.g.*, Rudajev 1993, Doležalová *et al.* 2008, Kaláb *et al.* 2009). The first mining induced seismic event was felt in 1912, originated in Hoheneger Mine, in the Ostrava region (*e.g.*, Martinec *et al.* 2006). The strongest rockburst in the Karviná region, with the magnitude $M = 3.8$, occurred in April 1983 in the ČSA mine. As many as 50 000 events are recorded in the Karviná region per year. About 100-500 events release seismic energy higher than 9×10^3 J (local magnitude equal to about 1.0). Strongest events may cause vibrations observed on the surface. In smaller epicentre distances, a damage of structures may be observed, *e.g.*, cracking of walls or plaster falling off, especially in the case of the strongest events.

The effects of mining induced seismicity on the surface in the area of Karviná are at present monitored by solitary seismic stations situated in selected objects on the surface. The seismic stations were installed by the Insti-

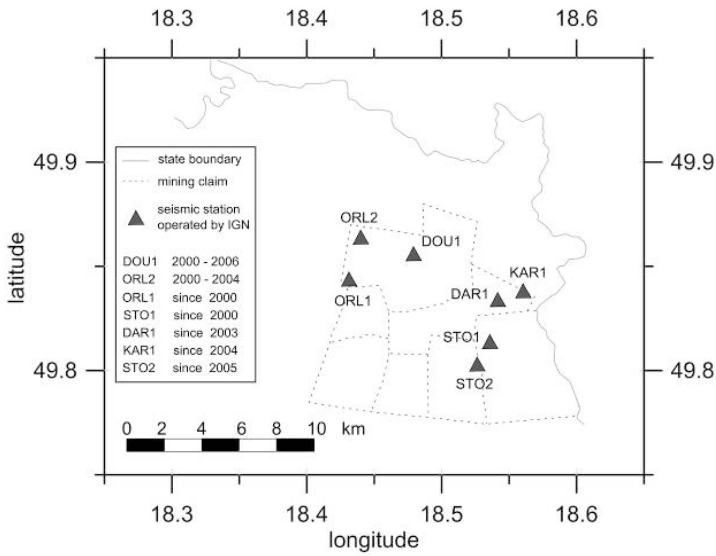

Fig. 1. Seismic stations operated by the Institute of Geonics in Karviná area.

tute of Geonics. This monitoring started in the years 1999-2000, when four solitary seismic stations were established in the areas of Orlová (signed as ORL1 and ORL2), Doubrava (DOU1), and Stonava (STO1). Three more seismic stations were established in the area of Darkov (DAR1) in 2003, in the area of Karviná (KAR1) in 2004, and in the area of Stonava (STO2) in 2005 (Fig. 1). Data from these stations have been recorded in a trigger mode after exceeding the pre-set level of the vibration velocity. Digital three-component instruments PCM3-PC and PCM3-EPC are used for measurements (Knejzlík and Kaláb 2002). The seismic stations are equipped with SM-3 seismometers oriented according to geographical coordinates. These apparatuses provide digital records of measured signals in the frequency range of 0.5-30 Hz and sampling frequency of 100 Hz. Measurement of rotational component of vibrations, using newly developed S-5-SR sensor, was also performed in Orlová and Doubrava localities (Knejzlík *et al.* 2012, Kaláb *et al.* 2013, Lyubushin *et al.* 2015). Results from seismological monitoring together with geotechnical studies are used also for evaluation of seismic loading of structures, *e.g.*, Kaláb and Lednická (2012).

3. GENERAL DESCRIPTION OF SUBSURFACE GEOLOGY OF THE INVESTIGATED AREA

The Czech part of the USCB (the whole basin area is approx. 1600 km^2) is situated on the northeastern edge of the Czech Republic and geologically it belongs to the segment of Variscide orogeny. The knowledge of deeper bedrocks of this basin is based on the drilling exploration and interpretation of regional gravity and seismic measurements. Upper Carboniferous strata represent hard rocks of basin including coal seams (Dopita *et al.* 1985). Carboniferous formations are buried with Quaternary and Tertiary sedimentary rocks. The thickness of these sedimentary rocks is variable (Fig. 2). The tectonic structure and stress conditions in USCB are described in detail in papers by Waclawik *et al.* (2013), Ptáček *et al.* (2012), and Grygar and Waclawik (2011). In the area of Karviná subbasin, the normal fault structures combined with the horizontal component of displacement and the significant thrust structures with a relative horizontal displacement to the order of hundreds of meters are encountered. These thrust structures form a complicated compression system defined as the Central Karviná Thrust and the Eastern Thrust.

In the vicinity of the town of Orlová is situated the Carboniferous basin elevation and it is called the Carboniferous window, in which Carboniferous rocks extend up to the surface. Results reporting and mapping both engineering-geological and drilling works show that local landfill and/or soils with thickness up to 1 m are placed in this area, which might cover loess or gravels up to a thickness of 3 m. Carboniferous rocks in this area are buried by

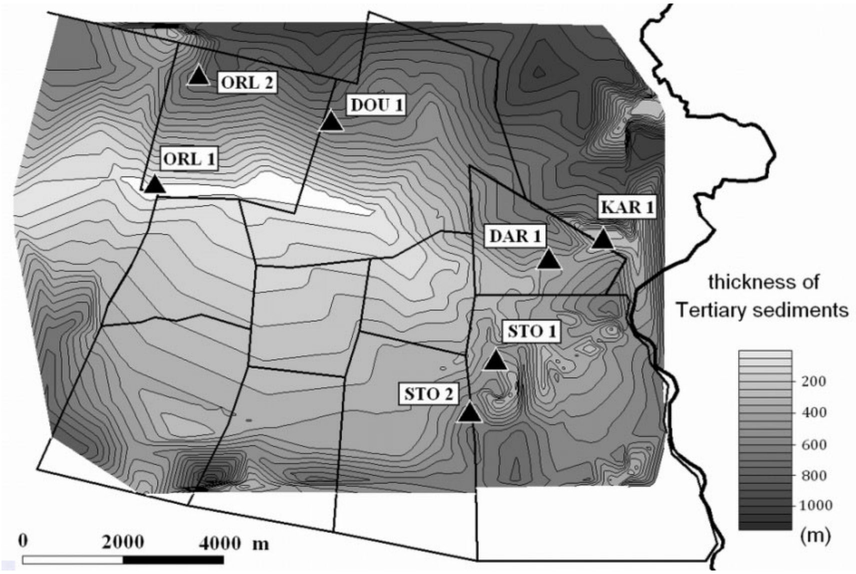

Fig. 2. Thickness of Tertiary sediments in the area of Karviná.

these loose sediments. High level of groundwater (in gravels partly also artesian water) is documented in the area.

Different subsurface geology is described around the Doubrava locality. First of all, the significant thickness of Tertiary sedimentary rocks, which reach 500 m, is located here. These sediments cover Carboniferous rocks. The sequence of consolidated and low consolidated clays, claystone, and sandstone with intercalations of other rocks (*e.g.*, limestone) composes these Tertiary sediments. Quaternary sandy silts and silty sands, clays, and alluvial sediments around streams are documented on the surface. The last-mentioned unconsolidated Quaternary soils on the surface change quickly and irregularly; they also have variable thicknesses and, therefore, an exact local subsurface geology can be determined by using local borehole only. This is also confirmed by the study of geological pattern in the vicinity of the Doubrava seismic station within the radius of 100 m where several types of subsurface geology were found in engineering-geological maps (Fig. 3).

The position of three selected boreholes is marked on the map (Fig. 3): a borehole signed as B1 near the ORL1 station, B2 and B3 near the DOU1 station. The data were obtained from the database of drilling documentation maintained by the Czech Geological Survey. The B1 borehole is located in the southeast direction of about 100 m from the ORL1 station. The landfill is documented to a depth of 2 m, below which is a layer of sand. At a depth of 5.4 m, Carboniferous rocks, consisting of sandstone weathered to a depth of

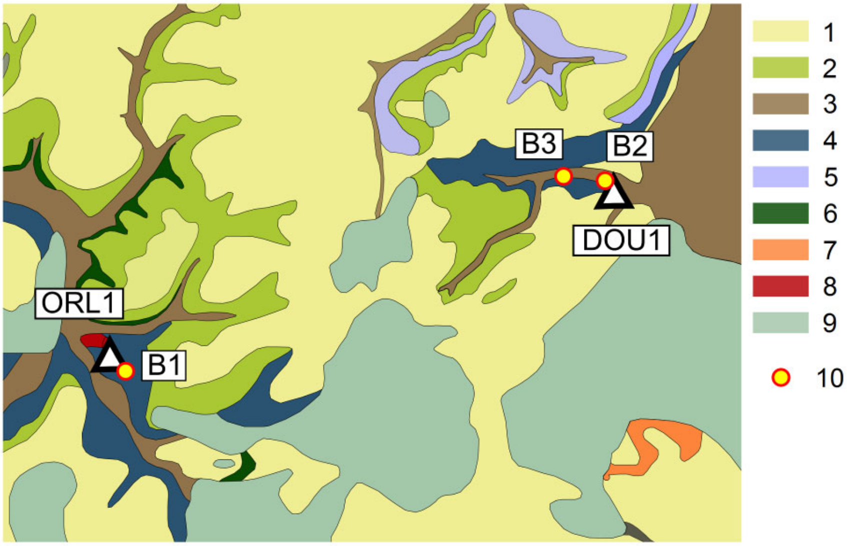

Fig. 3. Engineering-geological map of studied area with positions of selected boreholes. Legend: 1 – loess silt, 2 – clay and/or sand, 3 – silt, sand, sporadically gravel, 4 – sandy-silt or silty-sand, 5 – clay, 6 – calcic clay, 7 – sand and/or gravel, 8 – sandstone (Carboniferous rocks), 9 – landfill, 10 – borehole (B1-B3), triangle – seismic station.

7.5 m, are described. In the surroundings of the DOU1 station, only very shallow boreholes, to a depth of max. 10 m, were drilled, passing through Quaternary soils while their bottoms were in Neogene sediments. The closest two boreholes, B2 and B3, are located to the northwest direction at distances of approximately 50 and 320 m, respectively. The geological profile of closer B2 borehole consists of 0.5 m of landfill below which is stiff silt to a depth of 1 m. Clayey silt is documented below stiff silt to the final borehole depth of 10 m. In the place of the borehole B3, the landfill represents a layer of about 1.6 m thick, below which is soft silt to a depth of 2.5 m. Then to the final borehole depth of 10 m is clayey silt.

4. DATA ANALYSIS

The site effect evaluation in Doubrava locality is a subject of our study; analyses were made based on the data of the DOU1 and ORL1 seismic stations. Two methods were used for the data analyses, *i.e.*, Standard Spectral Ratio method (SSR) and Horizontal to Vertical Spectral Ratio method (HVSR). For the application of these spectral ratio methods we have used wave patterns of seismic events recorded simultaneously on the mentioned seismic stations.

4.1 SSR

The SSR method was described by Borcherdt (1970). This method is based on computing the Fourier spectral ratio of the same seismic waves simultaneously recorded by the horizontal components of two seismic stations, one of which is located on a bedrock outcrop. The main difficulty associated with this technique is the necessity of the existence of reference site which means the outcrop of bedrock. Moreover, the correct use of the SSR technique requires the distance between the test and reference site to be significantly smaller than the epicentral distance of recorded seismic event.

In our case, when evaluating the site effect in the area of Karviná region, we decided to use the ORL1 seismic station in Orlová locality as the reference site because the Carboniferous outcrop is located here (Fig. 2). The ORL1 station is located not directly at the outcrop, but in the distance of approximately 100 m from the outcrop. According to the borehole documentation, where the seismic station is located, Carboniferous rock is covered by a few meters of landfill and sand. Moreover, the first meters of Carboniferous rock are weathered. The existence of weathered rock layers may also result in the site effect (Steidl *et al.* 1996), so it will be necessary to investigate this possible effect, *e.g.*, through an evaluation of seismic events measured at the ORL1 station using HVSR method. As mentioned above, the first values of spectral ratio, obtained by HVSR method, were presented in the paper by Kaláb and Knejzlík (2006). HVSR method was applied on mining induced seismic events originated in the OKC. The spectral ratio values were very low at ORL1 station, almost 1.0 for the frequencies below 4 Hz.

The distance between the selected reference site (ORL1 station) and the test site (DOU1 station) is 3.9 km. Mining induced seismic events originated in the OKC have epicentral distances to the DOU1 and ORL1 stations only up to 12 km. Most of the events originate much closer. These distances are relatively short for the application of the SSR method. Therefore, we searched for stronger seismic events originated far from the stations, it means, from the Polish part of the USCB. During the operation of the DOU1 and ORL1 stations we found out only four of the events that were recorded simultaneously at both stations. Local magnitude range of these events is $ML = 2.9 - 3.7$ according the *Bulletins of Seismic Events Recorded by the Czech Regional Seismological Network* (www.czechgeo.cz). Localization of the stations and epicentres of selected events are presented in Fig. 4. Epicentral distances are more than 5 times longer than the distance between the test and the reference site, so the distance requirement for using the SSR method is fulfilled. An example of wave patterns of two recorded events is in Fig. 5. If we compare vibration effect at the ORL1 (black line) and DOU1 (grey line) stations on the vertical component, measured values of vibration

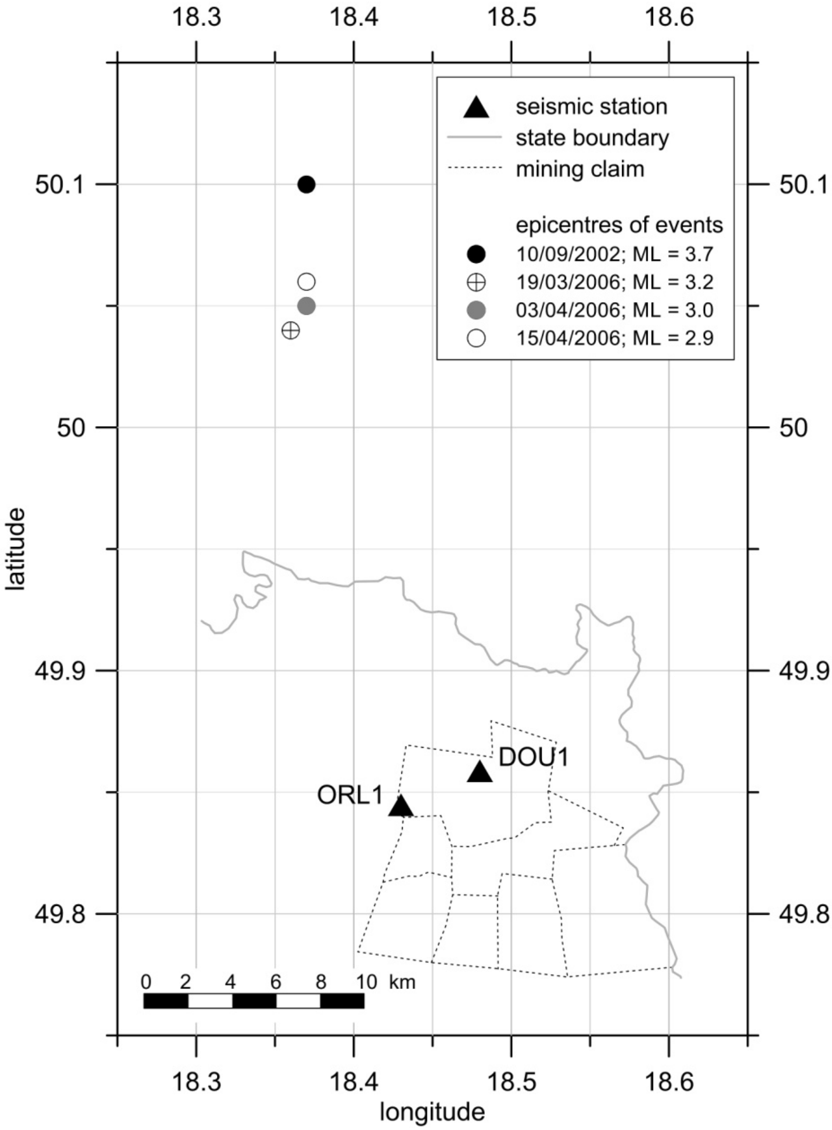

Fig. 4. Location of ORL1 and DOU1 stations and location of analysed seismic events' epicentres in a Polish part of the Upper Silesian Coal Basin (according the *Bulletins of Seismic Events Recorded by the Czech Regional Seismological Network*, www.czechgeo.cz).

velocity are almost the same. However, vibration effect at the horizontal components at the DOU1 station is significantly higher than at the ORL1 station, not only for the *S* wave, but also for the following wave groups.

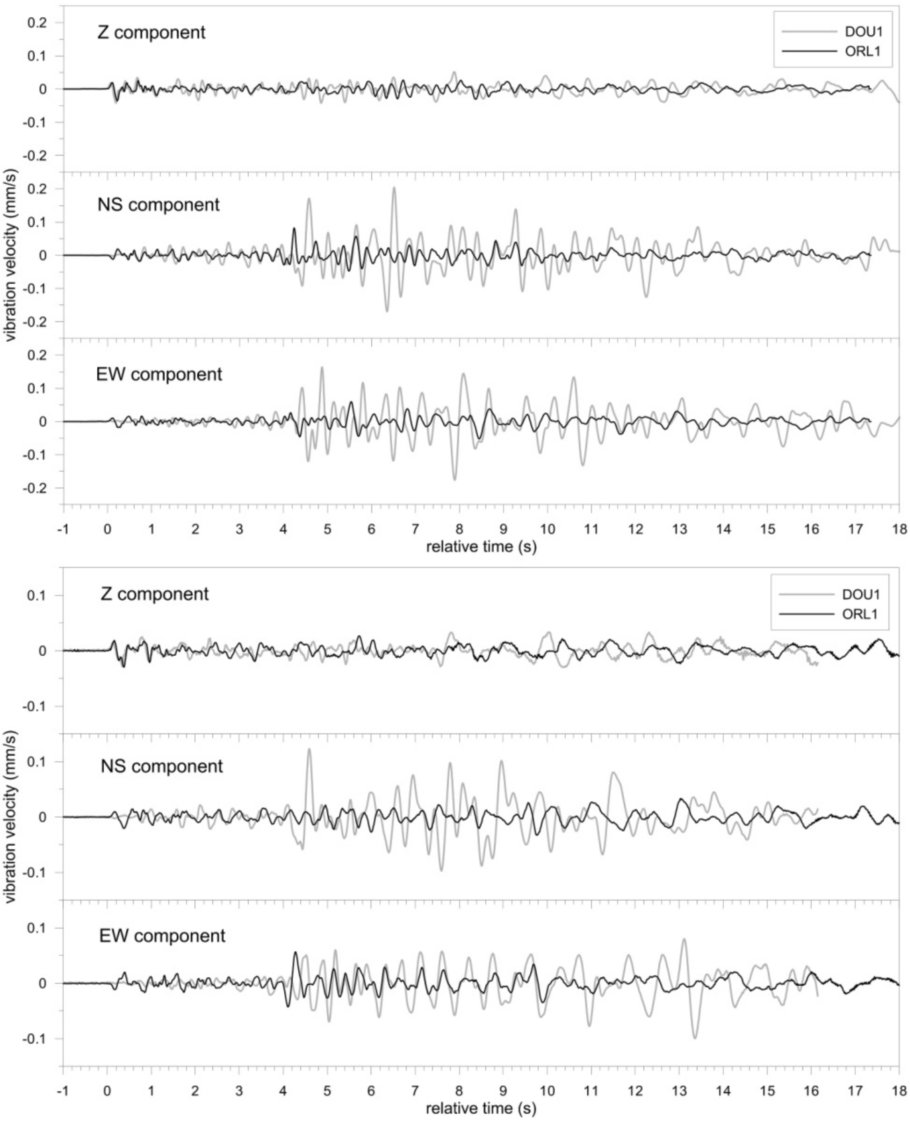

Fig. 5. Examples of wave patterns of two seismic events originated in a Polish part of the Upper Silesian Coal Basin (upper wave patter – seismic event occurring on 10 September 2002, with $ML = 3.7$; lower wave pattern – seismic event occurring on 15 April 2006, with $ML = 2.9$).

Records of analyzed events comprising all wave groups were used for the frequency analysis in this study. Spectra (S) for booth horizontal components (NS, EW) were calculated by using the FFT algorithm with Hamming

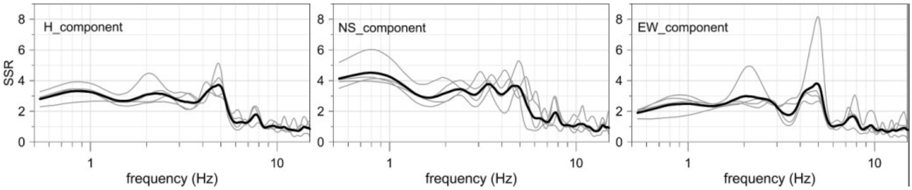

Fig. 6. Spectral ratio curves calculated for the station DOU1 using SSR method; the graphs show individual spectral ratio curves computed for all selected events (grey lines) and the averaged spectral ratio curve (black line).

window and obtained curves were smoothed with a spline function (Sigview software). These two horizontal spectra (S_{NS}, S_{EW}) were averaged to form one horizontal spectrum using geometric mean (S_H) for each station. After this, spectral ratios (SSR) were calculated by using spectra S_{NS}, S_{EW}, and S_H: $SSR_{NS} = S_{NS(DOU1)}/S_{NS(ORL1)}$, $SSR_{EW} = S_{EW(DOU1)}/S_{EW(ORL1)}$, and $SSR_H = S_{H(DOU1)}/S_{H(ORL1)}$. Resultant spectral ratios were geometrically averaged for four analysed events and results are presented in Fig. 6.

We can see that the spectral ratio curve calculated from averaged horizontal spectra has no only one significant frequency peak and the amplification is observed within the frequency range of 0.5-6 Hz, ratio values are within the range of 2.5-3.5. In this frequency range we can detect peaks at frequencies 4.9, 2.1, and 0.8 Hz. For the individual NS and EW components there is a difference in shape of spectral ratio curves. For the EW component the shape of curve is similar to the one of the H component. The peak at the frequency of 4.9 Hz is clearer, with the amplitude of 4.0. There is not so clear peak for the NS component. The highest amplitude of 4.5 is detected for the frequency 0.8 Hz.

4.2 HVSR

The same data set of seismic events originated in Polish part of the USCB was used for spectral ratio computation by using the HVSR method. This technique does not need a reference station and it is based on the computation of the horizontal-to-vertical spectral ratio, of the components of motion recorded at only one seismic station (Lermo and Chavez-Garcia 1993). This technique is founded on the assumption that the vertical component of motion is not affected by the local geological conditions (Panzera *et al.* 2013).

Spectra for vertical (S_V) and booth horizontal components (S_{NS}, S_{EW}) were calculated by using the FFT algorithm in the same way as for the SSR method. The spectral ratios (HVSR) were then calculated by using spectra S_V, S_{NS}, S_{EW}, and S_H for the ORL1 and DOU1 stations separately: *e.g.*, $HVSR_{H(DOU1)} = S_{H(DOU1)} / S_{V(DOU1)}$. The results are in Figs. 7 and 8.

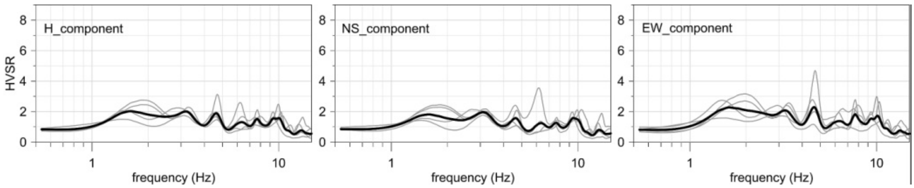

Fig. 7. Spectral ratio curves calculated for the station ORL1 using HVSR method; the graphs show individual spectral ratio curves computed for all selected events (grey lines) and the averaged spectral ratio curve (black line).

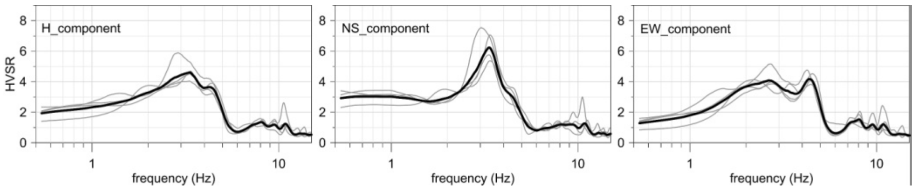

Fig. 8. Spectral ratio curves calculated for the station DOU1 using HVSR method; the graphs show individual spectral ratio curves computed for all selected events (grey lines) and the averaged spectral ratio curve (black line).

The results presented in Figs. 7 and 8 are much clearer than those of the SSR method. The peak with the amplitude of 5.0 is detected at the frequency of 3.2 Hz for spectral ratio curve calculated from the averaged horizontal spectrum at the DOU1 station. There is also a difference between the NS and EW components. For the NS component we can see one significant peak at the frequency of 3.2 Hz which is the same as for the H component, while for the EW component we can detect two peaks at frequencies of 4.2 and 2.7 Hz. The amplification is observed within the frequency range of 0.5-5.5 Hz. If we look at the results of HVSR for the ORL1 station, we can see quite flat curves of spectral ratios. They are practically the same for the H, NS, and EW components comprising several frequency peaks with the amplitude up to 2.0 for the frequency above 1.0 Hz.

The comparison of the results of used spectral ratio methods is presented in Fig. 9. The best agreement of shape of SSR and HVSR curves is detected or the EW component with the amplification in the frequency range below 5.5 Hz. There is a difference in the shape of SSR and HVSR curves for the NS component. HVSR method exhibits one clear peak at 3.2 Hz with the amplitude of 6.0. There is also a small peak at the frequency of 3.2 Hz for SSR method, but the amplitude is lower and also other peaks with the same amplitude can be found on the SSR curve. Shape differences are detected for the H component as well. Again the amplification is observed at the frequency range below 5.5 Hz.

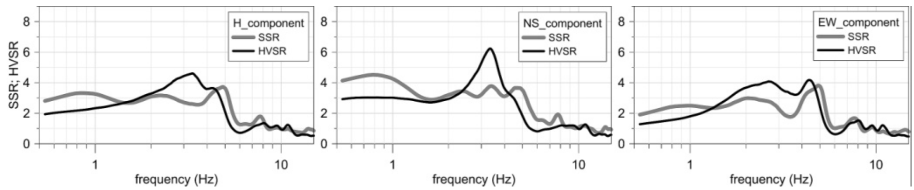

Fig. 9. Comparison of SSR and HVSR spectral ratio curves calculated for the DOU1 station. Averaged spectral ratio curves are used.

5. DISCUSSION

According to the presented results, there are differences in the obtained spectral ratio curves and also in the obtained values of frequency peaks and amplitudes. For both methods, the amplification in Doubrava locality is observed for the wide frequency range from 0.5 Hz (eigenfrequency of used sensors) to approximately 5.5 Hz. The most evident difference between the results of used methods is in the frequency range from 2 to 4 Hz.

According to Pitilakis (2004), both SSR and HVSR techniques are reliable in estimating the fundamental frequency of the soil profile. However, the amplification amplitude is comparable only when the soil layering is horizontal and there are no lateral geometrical variations. Moreover, the reference site has to be free of any kind of site effect.

Some differences in obtained spectral ratio curves may be caused by the selected ORL1 station as the reference site. This station is located almost at the Carboniferous outcrop and the vibration effect is much smaller than in Doubrava locality (Fig. 5). Nevertheless, there is a small effect of amplification that is documented from the HVSR curve calculated for this station. It means that the ORL1 station is not fully suitable as a reference site for the application of the SSR method in the Karviná area. In addition, the soil layering at the Doubrava locality is probably not horizontal.

A significant difference in spectral ratio curves observed on the two horizontal directions, NS and EW, is a next question. This difference should be considered as an anomaly in Doubrava locality because the HVSR method, performed for the ORL1 station, exhibits no differences in spectral ratio curves on the NS, EW and H components for Orlová locality. The difference between NS and EW components in Doubrava locality is probably caused by the complicated subsurface geological pattern in this place and irregular geometry of basement-deposit interface. This reason is documented using engineering-geological maps (see above). In addition, significant fault in the EW direction is located in this place. As mentioned in several studies, fault zones are anisotropic solids characterized by highly fractured zones and ground motion directivity is often documented in the vicinity of these zones (*e.g.*, Panzera and Vogfjörd 2014, Panzera *et al* 2014). Elaboration of ground motion directivity using seismic noise measurement was performed in other part of Karviná region – in Stonava locality (Lednická 2015). The measurement was realized in the zone of the Eastern Thrust and it was found that the determined maximum amplification corresponds to the direction of the horizontal component of stresses confirmed by the *in situ* stress measurements.

In order to make this discussion about site effect in Doubrava locality more precise, next experimental measurement is planned by using, *e.g.*, seismic noise measurements and horizontal to vertical noise ratio method for the evaluation including analysis of directional variations.

6. CONCLUSION

The topic of this paper was the evaluation of site effect in Doubrava locality, Karviná region. Doubrava locality is an urban area, where underground mining activities are still in progress and the vibration effect on the surface caused by mining induced seismicity is documented. From the geological viewpoint, Carboniferous rock massif is covered by Tertiary and Quaternary sediments of a thickness up to 500 m in this locality. Seismic events recorded on the surface seismic stations ORL1 (reference site) and DOU1 (test site) were used for the site effect analysis. Seismic events originated in Polish part of the Upper Silesian Coal Basin were analysed by the SSR and HVSR spectral ratio methods and the results of both methods were then compared. According to the presented results, there are some differences in obtained spectral ratio curves and in obtained values of frequency peaks and amplitudes as well. The results of the HVSR method are much clearer than the results of the SSR method and amplification derived from the HVSR curve is higher than the amplification derived from the SSR curve. Nevertheless, both methods proved the amplification effect at Doubrava locality within the same frequency range of 0.5-5.5 Hz. The significant peak with the amplitude of 5.0 is detected at the frequency of 3.2 Hz for spectral ratio curve calculated from averaged horizontal spectrum using HVSR method. The difference between spectral ratio curves for the NS and EW components was documented and this effect may be caused, *e.g.*, by complicated subsurface geological and tectonic pattern. It was found out that the ORL1 station is not fully suitable as a reference site if the SSR method is applied in the studied area of Karviná region, probably due to weak site effect in Orlová locality caused likely by weathered subsurface rock layers. Nevertheless, HVSR curves obtained for the seismic station ORL1 are almost flat compared to these curves calculated for the DOU1 seismic station. This result correspond well with the local geology, it means, the bedrock outcrop near the station ORL1 and thick sedimentary layers at the station DOU1.

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